FROM DEVELOPMENT AND QUALIFICATION TO PRODUCTION OF RICOR'S INNOVATIVE SWAP-C CRYOCOOLERS FOR HOT DETECTORS

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ABSTRACT

The improvement of IR detector technology achieved in the recent years enabled moving the operating FPA temperatures from 80K to a High Operating Temperature (HOT) around 150K and impelled development of innovative Cyrocoolers with low Size, Weight, Power and attractive Cost (SWaP-C).

Ricor's HOT family is based on five Cryocooler models: K527, K562, K562SI, K580 and K588, while two of the five are new Cryocoolers dedicatedly developed and optimized to operate at 130K-180K.

The paper reports on updated production performances of the K580 integral rotary Cryocooler and on a statistical performance mapping experiment that is running on a batch of eighteen K580 cryocoolers, based on a DOE (Design of Experiments) method, to map the Cryocooler working frequency dependency on different working conditions and to derive from the predicted frequency, the anticipated life span in specific working conditions.

The paper reviews the planning for an advanced Rotary version as a further step of excellence with "SWaP-C" parameters. K580I will be based on the K580 cryocooler enabling reverse compatibility and will introduce improvements by means of a new controller design with lower cost, reduced induced forces and with a narrower STD. It will also implement a sensor-less motor to reduce motor cost.

The paper reports on the progress made with the K588 split linear Cryocooler development and the configuration validated for the compressor with new controller and with two cold finger designs: a common cold finger and a customized cold finger.

The paper provides a report on the split linear Cryocooler performances, qualification status and accumulating operating hours on a pre-official life test. The current phase of the project resulted in attaining most of the specified parameters, while some of them still need further improvement in the next project phase.
The preparations for moving to the production phase are progressing, while the ramp-up is expected from mid 2020.

1. INTRODUCTION

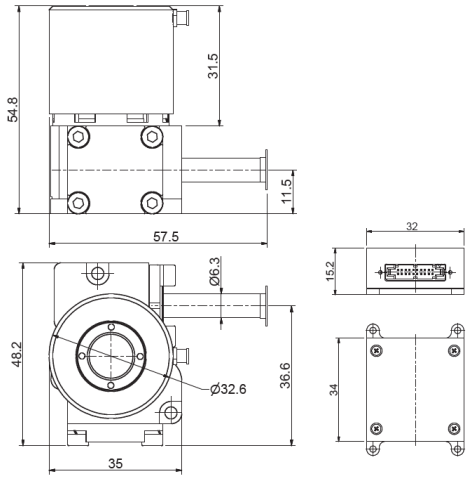
1.1. K580 integral rotary Cryocooler

The K580 is an advanced qualified integral rotary type cryocooler emphasizing the “SWaP-C” objectives. The cooler design concept was developed and constructed from scratch especially for the trend of HOT detectors, based on a new technology in order to reduce the optical axis length and to achieve an improved efficiency.
The reduction of this dimension was achieved by shifting the cold finger axis to the side of the cryocooler, while the thermodynamic aspects were designed by using Stirling cycle simulation software for optimal efficiency and minimal power.
The main parameters of the K580 model are listed in the table below:

Parameter	Typical Value
Cooling capacity	600mW@150K@71°C
MTTF	>16,000hr @basic profile
Regulated Input Power	1.5Wdc typ. (150mW@150K@23°C)
Max. Input Power	10Wdc typ.
Cool down time	3min typ. 150J@150K@23°C
Weight	Cooler - 190gr Controller - 30gr
Input Voltage	4-16 VDC
Ambient Temp.	-40˚C to +71˚C
Acoustic noise	non-detectability from 20m Level I

Table 1: K580 main parameters

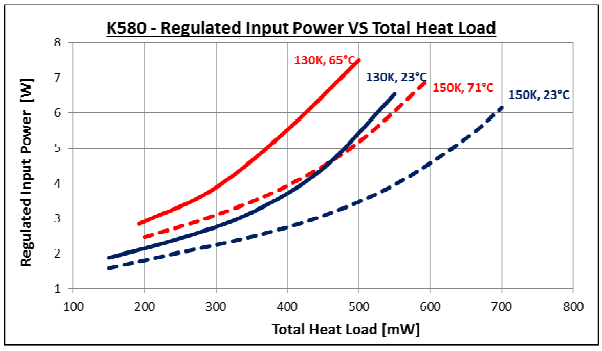
The K580 interface dimensions in Picture 1 emphasize the compactness achieved and the concept of shifting the cold finger axis from the motor axis to optimize cold finger length and thermodynamic efficiency. The cooler is qualified to operate with a 1/4" common cold finger.



Picture 1: K580 dimensions

The K580 is designed to operate in a wide range of cold tip temperatures from 130K up to 180K in order to feet with different types of HOT detectors.

Performances mapping was carried out at nominal helium fill pressure and 12Vdc at 130K and 150K at 23°C ambient and high ambient 65/71°C as shown in Graph 1:



Graph 1: K580 performances at 130K and 150K

The K580 driven by a new design of compact digital controller providing high efficiency, low weight, high temperature stability and compact mechanical structure.
The controller operates at wide range of input voltages and enables operating operation at two typical input voltages: 6Vdc and 12Vdc.

Following the main parameters of the K580 digital controller:

Parameter	Typical Value
Efficiency	>80% (Calculated, @>200mW)
Input voltage	4VDC – 16VDC (6V or 12V nominal operation)
Temp. stability	±0.1K
Temp. drift	±0.2K
Dimensions	34mm x 32mm x 15.2 mm
Weight	30gr
Com. protocol	RS422

Table 2: digital controller main parameters

1.2. K588 split linear Cryocooler

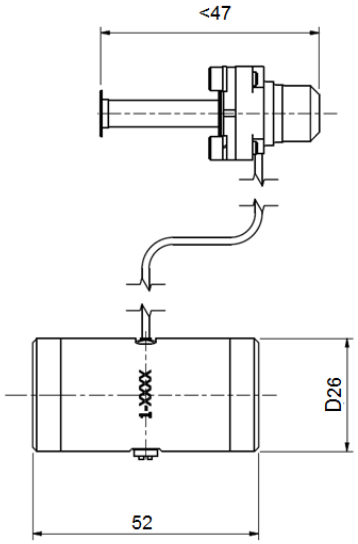
The K588 is an advanced linear type cryocooler emphasizing the “SWaP-C” objectives. The cooler design concept was developed and constructed from scratch especially for the trend of HOT detectors.
The design concept based on compact dual opposed compressor, all welded seal technology and moving magnet linear motors.
Following the main parameters of K588 model:

Parameter	Typical Value (design goal)
Cooling capacity	600mW@150K@71°C
MTTF	>30,000hr @basic profile
Regulated Input Power	2.5Wdc typ. (150mW@150K@23°C)
Max. Input Power	10Wdc typ.
Cool down time	1.75min typ. 150J@150K@23°C
Working frequency	110 Hz
Weight	Cooler - 200gr Controller - 10gr
Input Voltage	4.5-11 VDC
Ambient Temp.	-40˚C to +71˚C
Acoustic noise	non-detectability from 10m Level II

Table 3: K588 main parameters

Picture 2: K588 cooler

The K588 interface dimensions shown in Picture 3 emphasize the compactness achieved with the dual opposed compressor and the compact cold head using a 1/4" common cold finger as in the K580 model.



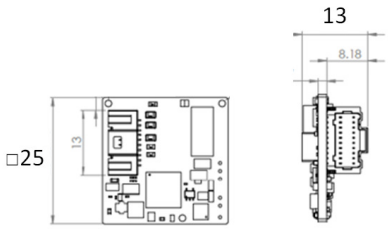
Picture 3: K588 interface dimensions

A new digital controller designed by using a novel approach to hardware and software development, providing significant achievement in terms of size, weight, performance and cost. Following the main parameters of the K588 digital controller:

Parameter	Spec. Value
Efficiency	78 – 90%
Input voltage	4.5VDC – 11VDC
Temp. stability	±0.1K
Temp. drift	±0.3K
Dimensions	30mm x 30mm x 19mm
Weight	10gr
Motor Frequency	40 – 140Hz
Max. Input Power	12Wdc typ.

Table 4: digital controller main parameters

Picture 4 emphasizes the compact digital controller dimensions achieved by implementing single double sided PCB.



Picture 4: K588 controller dimensions PCB

2. K580 DESIGN AND PERFORMANCES

2.1. K580 performances under production

The K580 cooler successfully completed HALT test, qualification at a different environmental and life demonstration test conducted at room ambient and was defined as a qualified cooler for HOT detectors.
The K580 cooler has moved from the development to production phase and few hundred coolers have already been manufactured while a ramp up plan for the coming years is being drawn up.

The following Tables 5 and 6 summarize the production performance of few hundreds of K580 coolers manufactured and tested in a climate chamber at different ambient temperatures:

Load [mW]	Average Input [Wdc]	STD Input [Wdc]	Ave. Temp. Stab. [mK]
185	1.74	0.31	±70
220	1.91	0.22	±90
320	2.35	0.10	±70

Table 5: K580 production performances @23°C

Load [mW]	Average Input [Wdc]	STD Input [Wdc]	Ave. Temp. Stab. [mK]
260	2.84	0.43	±70
340	3.45	0.33	±90
440	4.55	0.50	±100

Table 6: K580 production performances @71°C

2.2. Expanding life demonstration tests

A standard life demonstration test without acceleration was performed on six K580 coolers and resulted in a basic MTTF of more than 18,000 operating hours at a basic profile. The coolers tested at 23°C and stabilized to 150K cold tip temperature. The latest test results reported within reference [1].

In an additional step to test the reliability of the K580, a statistical performance mapping experiment was conducted and is still running with a large batch of K580 cryocoolers. The experiment is based on the DOE (Design of Experiments) method and plan to map the Cryocooler's working frequency dependency on different working conditions. The experiment aims to derive from the predicted frequency, the anticipated life span in specific working conditions.

The experiment life test includes 18 K580 coolers running at different accelerated conditions including 3 levels of helium pressure, 3 levels of skin temperatures and 3 levels of operating frequencies. The following Table shows the status of the running life test:

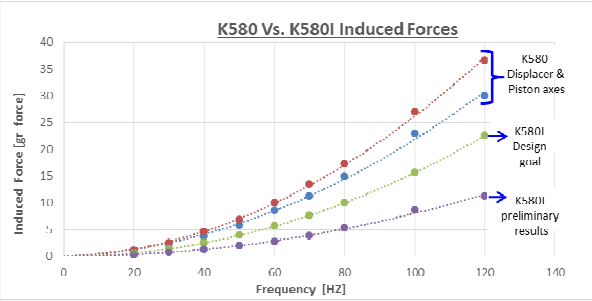
#	Pres.	Temp	Freq	hours	status
1	Level 1	Level 1	Level 1	7,691	running
2				7,799	
3		Level 2	Level 2	6,933	
4				7,543	
5		Level 3	Level 3	6,159	
6				5,821	
7	Level 2	Level 2	Level 1	7,530	
8				5,811	
9		Level 3	Level 2	5,018	
10				3,395	
11		Level 1	Level 3	5,871	
12				5,840	
13	Level 3	Level 3	Level 1	7,746	
14				7,111	
15		Level 1	Level 2	7,202	
16				7,219	
17		Level 2	Level 3	5,379	
18				3,438	

Table 7: Test levels of Pressure, Temp. and Frequency

2.3. K580I – improved version

As further step of excellence with "SWaP-C" parameters, an advanced version of the K580 is at the engineering level and has been named the K580I.
This version will be based on the K580 cryocooler enabling reverse compatibility and will introduce improvements by means of a new controller design that will cost less, reduce induced forces with narrower STD. It will also implement a sensor-less motor to reduce motor cost.

Following the improvement achieved with cooler induced forces comparing to standard version:



Graph 2: K580 Vs. K580I induced forces

Preliminary measurements of K508I induced forces show a significant potential reduction compared with the K580, <2 grf@40Hz which is around the typical operating frequency at 23°C and 150K with total heat load of 180mW.

3. K588 DESIGN AND PERFORMANCES

3.1. Compressor concept

Two different configurations developed in the framework of risk management. Both compressor versions developed to provide the same mechanical, thermal and electrical interfaces with challenging cylinder volume of 26mm diameter and 52mm length.
The first configuration is the more known and traditional one, based on the "all welded" seals, moving magnet linear motors and electrical feedthrough while the second configuration is designed with "all-welded" sealing, outside motor stators and with no need in feedthrough unit.

Both compressor versions analyzed for efficiency at resonance frequency (Eq. 3) derived from the dynamic model of motion equation (Eq. 1) and voltage equation (Eq. 2):

Eq. 1 $$m\ddot{x} + c\dot{x} + kx = \alpha I$$

Eq. 2 $$L\dot{I} + RI + \alpha\dot{x} = U$$

Where:

m – Mass
c – Compressor damping
k – Spring constant
α – Motor constant
I – Current
L – Inductance
R – Electrical resistance
U – Motor voltage
X – Displacement
Ẋ – Velocity
Ẍ – Acceleration

Eq. 3 $$\epsilon_{at\ resonance} = \frac{1}{1+cR/\alpha^2}$$

Where:

ϵ – theoretical motor efficiency at resonance

The following table 8 summarizes the tests perfromed for both compressor configurations:

Parameter	First configuration	Second configuration
Measured motor constant	4.6	2
Measured motor resistance	1 Ω	0.5 Ω
Compressor damping	7 Nm/sec	6 Nm/sec
Theoretical motor efficiency	75%	57%

Table 8: comparison of compressors efficiencies

The outcome of the measurements perfromed demonstrated advantage of more than 30% with the theoretical compression efficiency of the first configuration assuming negligible friction between the pistons and the cylinders. The following picture presents the chosen configuration based on “all welded” seals, moving magnet linear motors and electrical feedthrough.

Picture 5: compressor configuration chosen

3.2. Cold head concept

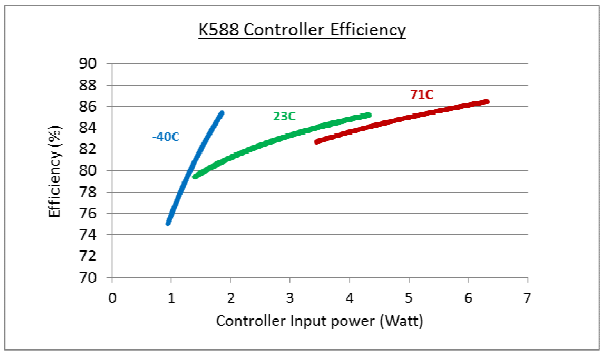
The all welded compressor designed can activate two different cold head designs. The first configuration is based on the common cold finger (31mm length) intended for variety of potential customers while the second configuration is based on a specific “short” cold finger, which exclusively designed for a specific customer.

Picture 6: common cold finger

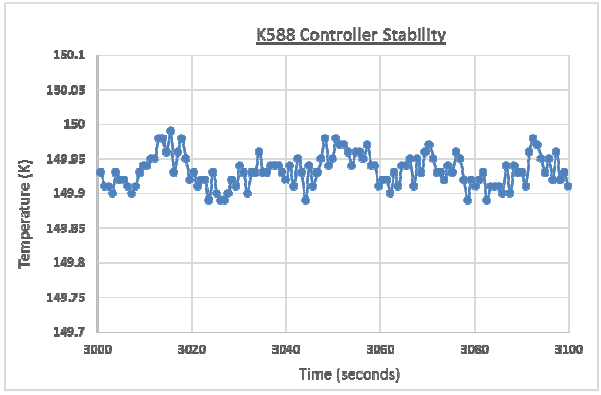
Picture 7: "short" cold finger integrated with compressor

3.3. K588 controller

The controller was designed by using novel approach of hardware and software development, providing significant improvements in terms of size, weight, performance and cost. Graph 3 presented the efficiency achieved at different ambient temperatures and Graph 4 presents high level of temperature stability measured at room ambient.



Graph 3: Controller efficiency at different ambient



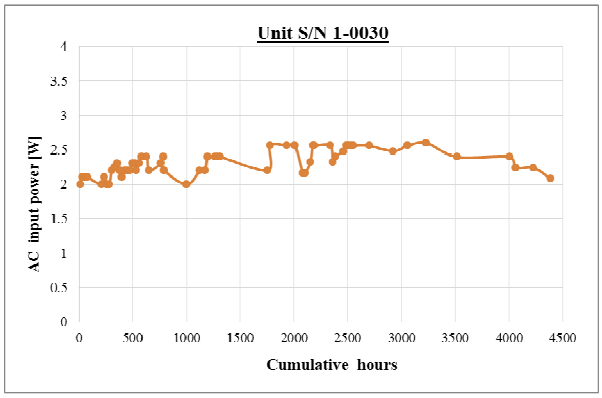
Graph 4: Controller temperature stability

3.4. Qualification, life test, HALT and On/Off

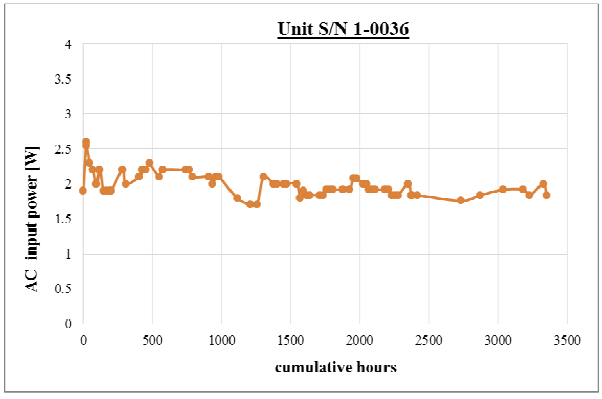
A pre-qualification test was successfully performed with a purpose to test and study the first prototypes. Such a test is a proper way to troubleshoot hidden problems at early stages, and eventually to make essential improvements of the initial design.

A full qualification plan for the compressor with "short" cold finger is under preparation while complementary tests will be perfromed in a second phase for the combination with common cold finger. The qualification will be perfromed on 3 units and will include high and low temperature profiles, thermal shocks, vibration tests, mechanical shocks, humidity, altitude, induced forces and acoustic noise measurements.

As a pre-life test, two compressors integrated with "short" cold finger under testing at room ambient and keep accumulating operating hours by monitoring the regulated power consumption as shown in graphs 5.1 and 5.2:



Graph 5.1: Pre-life test, first unit



Graph 5.2: Pre-life test, second unit

A full life demonstration test is planned on 6 units that will be tested in two groups, each group will be exposed to a different test profile. Every 3,000 operating hours accumulated, the units will be tested for leak rate, acoustic noise, induced vibration and cryogenic performances at different ambient.

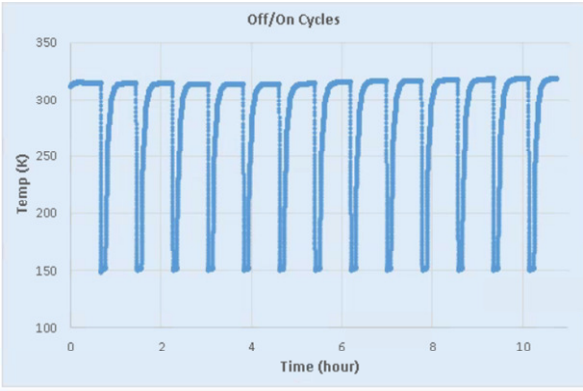
The expected MTTF is to achieve more than 30,000 operating hours at basic profile which is based on more than 43,000 operating hours achieved within running life test on K527 model that include quite similar upscaling design concept.

In addition, the K588 controller successfully passed HALT test by exposure to extreme ambient, temperature cycling and combined thermal cycling with Radom vibration up to a level of 18gRMS. Table 9 presents summary of the tests perfromed during the HALT test.

Test Environment		Test Description	Test Result	Remarks
Temperature [°C]	Vibration			
Minimum temperature	None	-50 °C	O.K.	
Maximum temperature	None	+70 °C	O.K.	
20 °C (room temperature)	Maximum gRMS	+18.0 gRMS	O.K.	Manually Stopped
Temperature cycling	None	-40 °C to+70 °C	O.K.	
Temperature rate per min.		40 °C	O.K.	
Combined cycling	18.0 gRMS	-40 °C to+70 °C	O.K.	
Minimum temperature ramp	0.5 * maximum gRMS	-30 °C	O.K.	
Maximum temperature ramp	0.5 * maximum gRMS	60 °C	O.K.	
Maximum cold start temperature		-50 °C	O.K.	

Table 9: Summary of HALT test

An On/Off test that accumulated few hundreds of cycles keep running on 2 compressors integrated with "short" cold fingers at room ambient. The test monitor performances repeatability and stability of operation as shown in picture 7:



Picture 7: On/Off cycling test

4. SUMMARY

The new Ricor's innovative linear and rotary cryocoolers for HOT detector are well progressing from development and qualification to the production phase and providing advantages with SWaP-C parameters for new thermal imagers.

The "all welded" highly compact compressor of K588 model and the advanced rotary compressor of K580 model are comply with the common cold finger and provide flexibility and intractability for the detector manufacture.

Ricor keep improving the crycoolers as perfromed with K580I version by reducing the induced forces and optimizing cost as a further step of excellence with "SWaP-C" parameters.

5. REFERENCES

[1] Oron Ben David, Meir Carmiel, Victor Segal, Igor Vainshtein, Sergey Riabzev, Avishai Filis “Ricor's Advanced Rotary Cryocooler for HOT IR detectors", SPIE conference (2019)

[2] Sergey Riabzev, Dmitry Radchenko, Dror Raf, Ilan Nachman, Sergey Sobol, Dan Gover "RICOR’s new development of HOT cryocoolers: compact cost-effective linear model", SPIE conference (2019)